INVESTIGATION OF THE IMPLEMENTATION OF RAMP REVERSAL AT A DIAMOND INTERCHANGE

A Thesis

by

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ABSTRACT

Diamond interchange design has been commonly utilized in United States to facilitate traffic exchange between freeway and frontage roads. Another less common interchange design is X-ramp interchange, which is the reversed version of diamond. The major benefit of X-ramp interchange is that it can keep travelers on the freeway until the downstream exit ramp to avoid going through the intersection. It also has drawbacks such as travelers with cross street destinations will experience more delay. This study focuses on when the ramp reversal is desirable. To compare the diamond and X-ramp design, an experimental design is conducted using Latin Hypercube Design method. Four varying factors include interchange design type, traffic volume on the frontage road, through movement percentage and saturation rate of the intersection. 40 scenarios are generated for simulation study using Synchro and VISSIM.

Based on the simulation study, optimal signal timing strategies are recommended for each type of interchange design under various traffic conditions. Also, ramp reversal is found closely related to the following factors such as interchange frequency, upstream interchange design, traffic volume on frontage road, through movement percentage and intersection saturation rate. Conclusions are made on when X-ramp is better than diamond interchange design. At last, future research directions are recommended.

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Thanks also go to my friends and colleagues and the department faculty and staff for making my time at Texas A&M University a great experience. I also want to extend my gratitude to the Texas Transportation Institute, which provided the survey data of SH 6 @ Harvey Rd interchange for simulation model development in this study.

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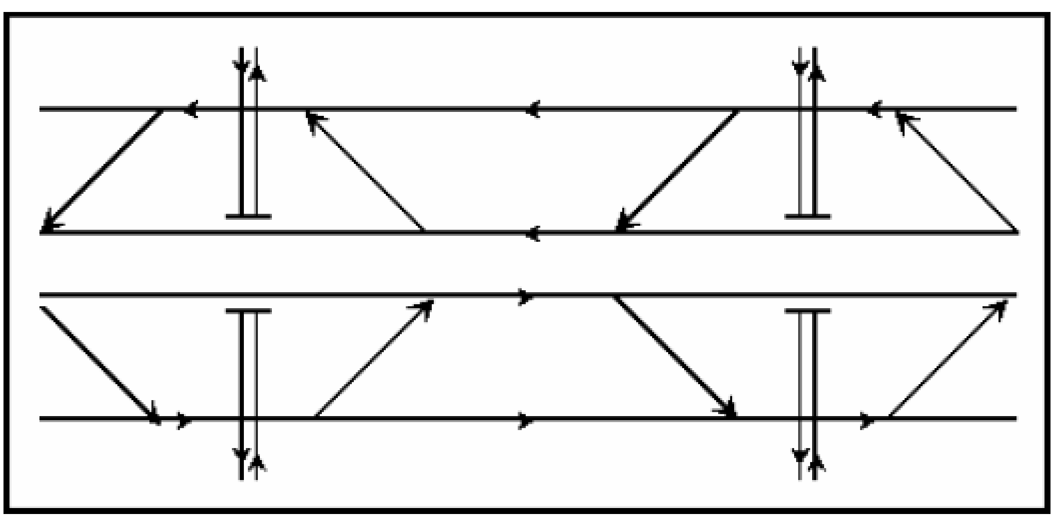
CHAPTER I

INTRODUCTION

1.1 Diamond Interchange and X-ramp Interchange

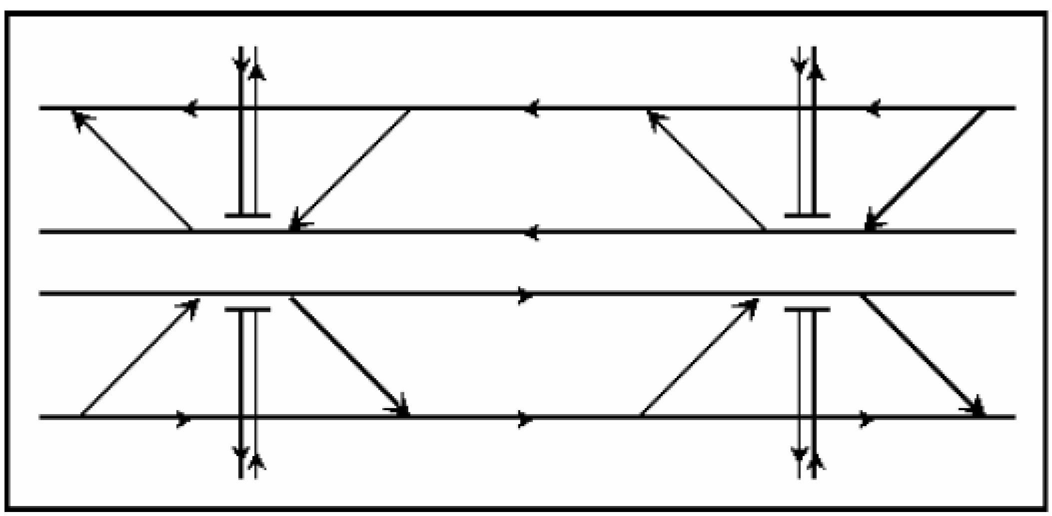
An interchange is a road junction that typically uses grade separation, and one or more ramps, to permit traffic on at least one highway to pass through the junction without directly crossing any other traffic stream *(Chlewicki, 2003)*. Diamond interchange design is often utilized in Texas to facilitate traffic exchange between freeway and frontage road. In a conventional diamond interchange design, or Y-ramp interchange, exit ramp is located upstream of an entrance ramp. Figure 1 shows the shape of two diamond interchange, from which we can find that this type of interchange design get its name because it shapes like a diamond.

Figure 1 Conventional Diamond Interchange Layout (Not to Scale).



Eventually, researchers realized that in some scenarios, it would be beneficial to reverse the exit ramp or the entrance ramp. Ramp reversal is defined as to replace an exit ramp with an entrance ramp or vice versa. If all four ramps in a typical diamond interchange are reversed, then it becomes an X-ramp interchange. Figure 2 shows the shape of X-ramp interchanges. In an X-ramp interchange, the exiting ramp locates at the downstream of the entrance ramp, which is just the opposite of a diamond interchange. And this is the main difference between those two interchange design types in terms of geometry.

Figure 2 X-Ramp Interchange Layout (Not to Scale)



1.2 Research Motivations

Population growth and vehicle ownership increase has placed tremendous burden on freeway systems, especially in urban areas. The cost of constructing new facilities or expanding existing ones has become too expensive to afford. When road expansion becomes less possible, many states' Department of Transportation (DOT) tries to seek for new approach to maximize freeway capacity and efficiency. Modification of current freeway elements is one way of avoiding high construction cost while resolving traffic congestion. One important and effective approach is to modify ramp configurations via ramp relocations and ramp reversal. It often can help reduce vehicle queues at critical locations, redirect traffic to avoid signals, and thus mitigate roadway congestions. One common way of ramp modification is ramp reversal at diamond interchanges.

Diamond interchange design is widely used throughout United States to facilitate vehicle exchanges between freeway and frontage road. However, diamond interchange design has its drawbacks such as heavy demand on frontage road, queue storage issue between exit ramp and signalized intersection, etc. Some researchers believed that through ramp reversal or ramp relocation, such problems could be resolved. To better investigate the benefit of ramp reversal, theoretical and practical studies had been conducted by researchers at Texas Transportation Institute *(Cooner, 2007)*. Nevertheless, the problem of when and where to use an X-ramp design as opposed to the more conventional diamond ramp design for freeway interchange has not been resolved adequately.

No existing research has been found engaging on the investigation of traffic demand and pattern's impact on interchange design type selection. However, the major difference between diamond interchange and x-ramp interchange is reflected on accessing the nearby facilities. The most beneficial part of X-ramp design comparing to diamond is its capability of removing the traffic load at several upstream locations without requiring motorists to pass through a series of signalized intersections. Thus, to determine which design to use, the major issue is to investigate the demand conditions around the interchange.

1.3 Problem Statement

One of the major benefits of X-ramp interchange is to allow vehicles to avoid the signalized intersection on frontage road, and thus dramatically decrease control delay. However, to ensure this benefit, the destination of the vehicle has to be located downstream of the signalized intersection. If its destination is located upstream, then such maneuver is undesirable. Therefore, the major factors that determine which type of interchange is beneficial are traffic demand pattern and demand level. While the previous studies by TTI researchers tried to develop guidelines for ramp reversal projects, little effort has been carried out to find the traffic demand's influence on interchange design. Also, no signal timing strategies were recommended for the reversed diamond interchange design.

A microscopic simulation analysis should be conducted to compare both interchange designs under different traffic demand scenarios. This simulation technique mimics the real world situation on a computer, gives the flexibility of different scenario designs, and offers the opportunity of projecting the consequence of the alternatives even before actual implementation. In addition, it is time and cost efficient, and risk-free. Thus, this research is designated to determine the benefits of ramp reversal under different scenarios with the help of simulation, and in what kind of demand conditions, ramp reversal is desirable. Plus, the researcher will investigate different interchange signal timing strategies to find out the one that suits X-ramp design the best.

1.4 Research Objectives

The main goal of this study is to determine when and where an X-ramp interchange design is more desirable than the conventional diamond interchange design by analyzing the influence of traffic demand pattern on interchange operations using microscopic simulation technique. The research objectives are:

- To model the existing diamond interchange using microscopic simulation software and to calibrate the model using field data,
- To use the model to simulate traffic operation conditions of an X-ramp interchange by reversing ramps,
- To vary the traffic demand pattern and demand level in the model and analyze the effect of different flow ratios on interchange operations, and
- To recommend the optimal signal timing strategies for X-ramp interchange design under various scenarios, and
- To identify the cost and benefit of ramp reversal under various conditions in financial units, and
- To make a recommendation on when a ramp reversal is desirable under different flow patterns and flow levels.

1.5 Thesis Organization

Chapter 1 introduces some basic concepts that will be discussed in this research such as diamond interchange, X-ramp interchange and ramp reversal. This chapter also states the research motivation and the problem that has been studied, and the objectives of this research.

Chapter 2 will summarize background information and previous researches about signal timing strategies for diamond interchange, diamond interchange operations, and ramp reversal.

Chapter 3 will introduce the microscopic traffic simulation software – VISSIM. Procedures and data used to develop the simulation model in VISSIM will be demonstrated. Calibration process of the model will be shown.

Chapter 4 will introduce the signal timing optimization software – Synchro, and the procedures to optimize signal timing plan.

Chapter 5 will introduce the Latin Hypercube Design method used to conduct experimental design. It also will show how the number of simulation runs for each scenario is determined. Plus, the simulation results from Synchro and VISSIM will be shown and discussed.

Chapter 6 will conclude what has been done and recommend the optimal signal timing strategy for each scenario. Essential factors that will influence the selection of a diamond design or an X-ramp design will be explained. Future research recommendations also will be made.

CHAPTER II

LITERATURE REVIEW

2.1 Signal Timing Strategies for Diamond Interchange

Being the most popular interchange design in U.S., diamond interchange operation has been extensively studied by numerous researchers. Messer and Berry *(1975)* examined the effects of minimum phase length and variations in spatial arrangement of ramp intersections on the capacity of diamond interchanges operated with 4-phase-overlap signalization. The FORTRAN IV was developed for their analysis, and they found that minimum constraints on phase lengths could have a significant influence on the interchange operation. Messer, Fambro, and Richards *(1977)* described a simulation program PASSER III developed for the Texas State Department of Highways and Public Transportation, and this program could determine the best strategy for a pretimed signalized diamond interchange to minimize the average delay.

Engelbrecht and Barnes *(2003)* did some research on advanced traffic signal control for diamond interchange. They found that the separate intersection diamond control mode is very useful under specific conditions. Lee et al. *(2003) (2006)* extensively evaluated how actuated signal control worked on diamond interchanges. Their study showed that the delay of each strategy (two phasing and three phase operation) was dependent on the traffic pattern, but there was a distinct movement preference for each strategy. Bonneson et al. *(2000)* evaluated alternative control sequences and settings for the actuated, three-phase diamond interchange. After a combination of theoretical analysis and an examination of diamond interchange phasing and traffic flow patterns, the guidelines for establishing controller settings that would generally yield low-delay operation were developed. Irvine and Fambro *(1992)* provided guidelines and procedures for the retiming of diamond interchanges. They included all the details about how to conduct data collection, and the analytical procedures and software packages that were available for signal retiming.

On the other hand, no research was found to carry out an investigation on signal timing strategies for X-ramp interchange design. This research will try to determine the suitable timing strategy under various scenarios based on simulation results.

2.2 Diamond Interchange Operation

Elefteriadou, et al *(2005)* developed a methodology for evaluating the operational performance of interchange. In their research, they realized that different interchange types can influence the turning movements, and thus origin-destination (OD) demands through the interchange should be considered. Throughout their study, instead of the volumes of each movement, the OD demands were controlled when designing their simulation scenarios. Unfortunately, X-ramp design was not in their selection pool, and they only focused on at-grade intersections but not on the freeway proper. Garber and Fontaine *(1999)* developed a guideline for optimum interchange type selection for a specific location. They did an extensive survey of existing interchanges in Virginia and a computer simulation based multi-case study was conducted to determine which type was best suitable in which situation.

Nowlin et al *(1996)* conducted a study to investigate the weaving operations on the frontage roads. Through extensive study of the two-sided weaving maneuver on the frontage roads, a procedure to determine the exit ramp-to-intersection spacing was developed. Gattis et al *(1988)* conducted a study in attempt to define the problems associated with frontage road conversion from two-way to one-way operations. Poisson arrival process and queuing theory were used to derive predictive models of delay for the selected cases. Their model was mainly established based on collected data. After validating their proposed model using the collected data, they found the relationship between delay and hourly ramp volume, frontage road capacity and frontage road flow rate.

2.3 Microscopic Simulation

It is always challenging to analyze and evaluate the performance of the transportation system before the implementation of new strategy or physical change. The most widely used transportation engineering guidebook, Highway Capacity Manual (HCM), can't provide a detailed and sufficient analysis. Sometimes, it may hardly be helpful in complicated situations such as ramp reversal. Thus, alternatively simulation becomes a valuable aid in assessing the performance of transportation system. Currently, a number of microscopic simulation software has been produced to model real-world traffic condition. However, calibration needs to be done before a microscopic simulation model can generate unbiased results.

Sufficient data is needed to prepare a simulation model. Some data (e.g. geometric design, traffic volume, travel speed) is easy to obtain, but some (e.g. driver behavior, desire speed) are rather difficult to observe from field study. A common practice is to calibrate those microscopic parameters using macroscopic performance measures that are much easier to observe. In sum, the process of adjusting and fine-tuning model parameters by using real-world data to reflect local traffic conditions is model calibration *(Park and Qi 2005)*.

Rigorous calibration is quite complex and time-consuming considering the many parameter combinations. Some users can adapt a certain number of parameters based on experience to make the model behave well, but this 'calibration' is rather opportunistic than systematic. Park and Schneeberger *(2003)* proposed a general calibration procedure based on a linear regression model. However, they fail to consider the combined effect of those parameters. In order to investigate the correlation of parameters, a Generic Algorithm (GA) has been introduced into this area.

GA is an optimization method that mimics the mechanism of natural selection and evolution *(Goldberg, 1989)*. Its robustness is due to its ability to perform a search from multiple points. Therefore, GA can take the combined effect between parameters into consideration, and it can reduce the risk of converging to local minima instead of global minima. GA has been successfully applied to many aspects of transportation engineering: traffic flow simulation modeling *(Araujo, 2008)*, traffic signal timing *(Teklu, 2007)* and even infrastructure maintenance planning *(Liu, 1997)*. GA also was introduced to simulation calibration by Cheu et al. *(1998)* to search for the optimal solution for parameter combinations.Although GA can be used for mass search, instead of a blind search; a sensitivity analysis can reduce the work load. Park and Qi (2005) adopted a statistical experimental design approach to reduce the number of combinations and also considered feasibility of the initial ranges of calibration parameters. These approaches also were used in this study to improve the efficiency of calibration process.

2.4 Ramp Reversal

Cooner et al *(2007)* conducted an extensive research on ramp reversal projects. In their research report, they explained the main reason for ramp reversal was to improve existing freeways with less expensive methods. A brief summary of the state-of-the-practice literature review was performed, and interviews and surveys focus on obtaining information on planned and previously implemented projects that involved ramp reversal was conducted. 15 sites were selected and evaluated based on the operational, safety, and basic economic impacts resulting from the ramp modification projects in the case study. Based on relevant evaluation criteria, the results of previous research, case study findings, and simulation data, a project evaluation process was outlined. Also, 21 guidelines and a checklist that should aid advance project development engineers in the planning and implementation of successful ramp reversal and X-ramp projects was provided. However, this guideline is proposed based on multi-case study, and no thorough consideration of possible traffic demand and flow levels are presented in their research.

Borchardt and Chang *(1986)* investigated several aspects of both diamond ramp design and X-ramp design in a very detailed manner. Field studies of existing configurations, aerial photographic survey and extensive simulation analysis were used in their research. In field study, they collected data at different sites of each design with ramp spacing throughout a desired range (800 ~ 3000 ft). Volume counts were conducted at each site during peak and off-peak hours for the following movements: freeway main lane throughout, entrance ramp volume, exit ramp volume, frontage road volume at ramp junctions, and intersection turning movements. In the simulation analysis, two kinds of software were used. The PASSER III analysis was used to provide optimized traffic signal control for different sets of geometric, traffic volume, ramp spacing designs. The NETSIM analysis was then used to study the detailed operational effects on the two types of ramp designs after excluding the traffic signal timing effects. Simulation results showed that X-ramp designs were associated with less overall delay than the diamond interchange designs.

However, this difference is not practically significant. In the conclusion of this article, the authors mentioned that those two different types of ramp designs do have some differences in term of access the nearby facilities. The major benefit of the X-ramp design is its capability of removing the traffic load at several upstream locations without requiring motorists to pass through a series of signalized intersections. Thus, to determine which design to use, the major issue is to investigate the demand conditions around the interchange.

CHAPTER III

MICROSCOPIC SIMULATION

The first step of this study is to model the interested interchange using microscopic simulation software. The simulation software that has been chosen in this study is VISSIM. The TX-6 Frontage road and the Harvey Road will be coded into the model according to their geometric design. Four ramps that constitute a diamond interchange will also be modeled in the simulation. Traffic flow and speed information and signal timing plan from field collection will be the initial inputs of the model in VISSIM.

The next important step is to calibrate the model. For a simulation to work in a way as we expect it to, whether the established model can represent actual situation in an acceptable level needs to be checked. To perform calibration, vehicle travel time from the entering point of the network to the exiting point will be selected as performance measure. By adjusting model parameters (mostly the parameters of car-following model and lane changing model), the researcher want to decrease the discrepancy between the actual travel time and the estimated travel time from simulation model to an acceptable level. Once the model is calibrated, it will be ready for simulation of real conditions.

3.1 Microscopic Traffic Simulation Software -- VISSIM

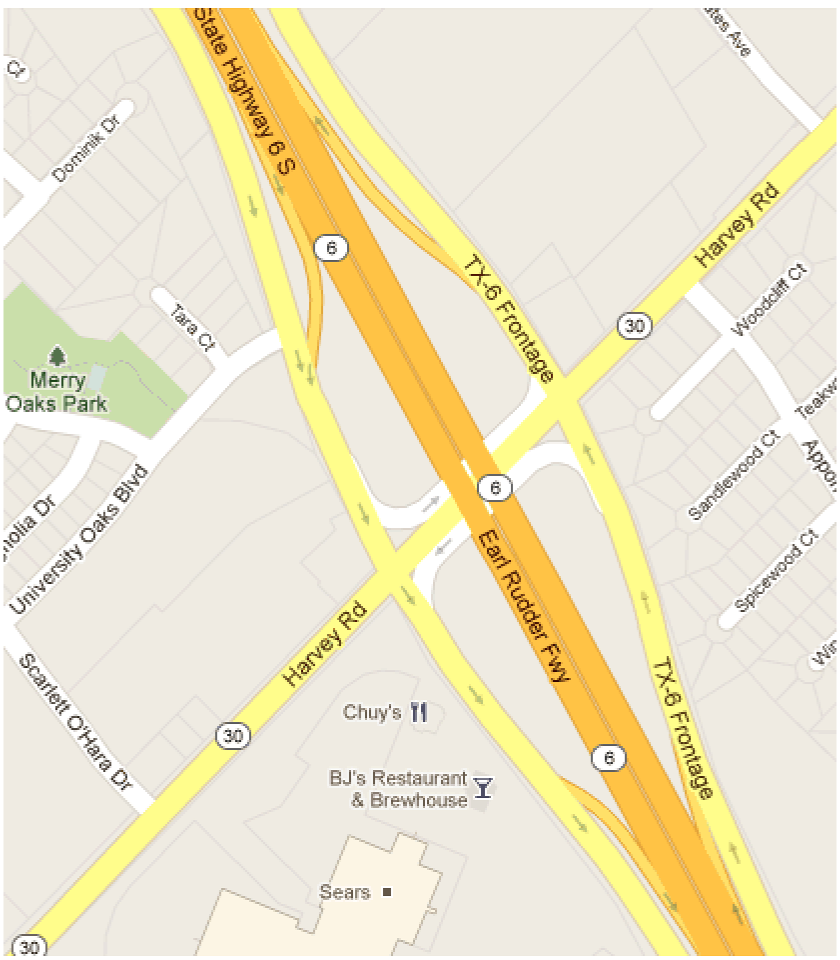
Microscopic traffic simulation is a computer based traffic analysis tool, which simulates the movement of individual vehicles according to car-following and lane-changing theories. Microscopic traffic simulation is very helpful especially when the situation that needs to be dealt is too complicated to analyze using traditional method. Through many years of development, there have been many different types of simulation software to choose in commercial market. Famous microscopic traffic simulation software includes: Aimsun by Transport Simulation Systems, CORSIM by Federal Highway Administration & University of Florida, MITSIMLab by Massachusetts Institute of Technology, TransModeler by Caliper Corporation and so on *(Algers, 2009)*.

The microscopic traffic simulation software that used in this study is VISSIM developed by PTV Inc. VISSIM is a microscopic, time-step and behavior based multi-purpose traffic simulation package, which was developed at the University of Karlsruhe, Germany during 1970s *(VISSIM User Manual, 2004)*. It is capable of simulating traffic operations on urban streets and freeways, with a special emphasis on public transportation and multimodal transportation.

3.2 Simulation Data

In order to illustrate the benefits of X-ramp interchange design, the Earl Rudder Freeway and Harvey Road interchange in College Station is selected as case study (Figure 3). Earl Rudder Freeway (State Highway 6) is the expressway that passes through Bryan-College Station area, and heavy traffic demand can be expected on this highway. Also, many business and commercial attractions like Post Oak Mall is located around this interchange. Thus large traffic exchange on those ramps will happen. Currently, the conventional diamond interchange design is applied at this site. However, Brazos County Metropolitan Planning Organization has proposed a plan to reverse the ramps of this interchange and turned it into an X-ramp interchange. Above all, this interchange can serve as a good case study, and can provide practical lessons for other similar ramp reversal projects. Also, it can be used as a case for simulation model development and calibration.

Figure 3 SH6 @ Harvey Road Interchange



To investigate the interchange between Earl Rudder Freeway and Briarcrest Drive, the following data needs to be gathered:

- Geometry information of the interested interchange,
- Signal timing plan of the diamond interchange,
- Traffic flow volume around the interchange,
- Vehicle speed on the freeway, frontage roads and crossing road,
- Vehicle travel time on the frontage road.

3.3 Simulation Model Development

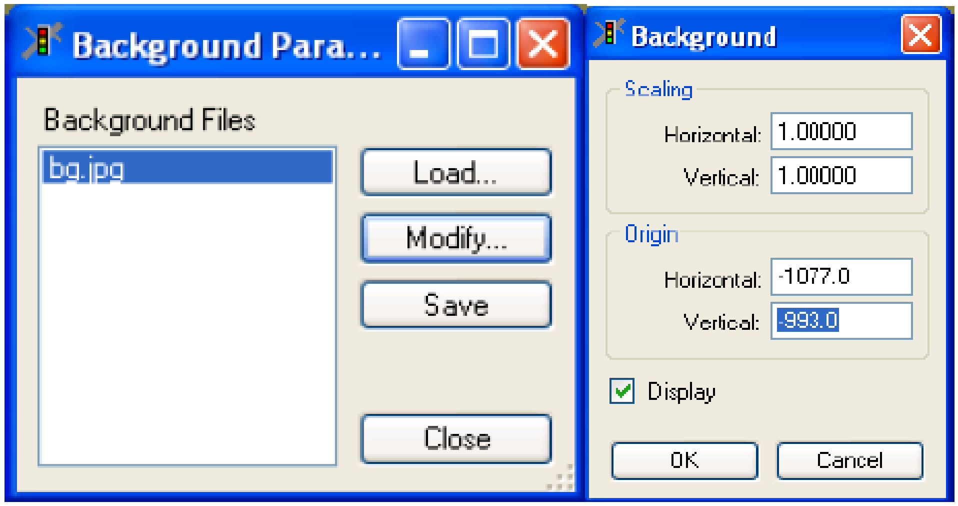
To build a simulation model in VISSIM for analysis, one has to code the following components into the model:

Traffic Network Components

<u>Scale</u>

As mentioned before, the geometry design of the model will use the data from SH 6@Harvey rd interchange. So the snap shot taken form Google map will be used as background in this model. Before starting to code the network accordingly, we have to check the scale in order to represent real-world conditions. Figure 4 shows the parameters for loading and modifying the background in VISSIM.

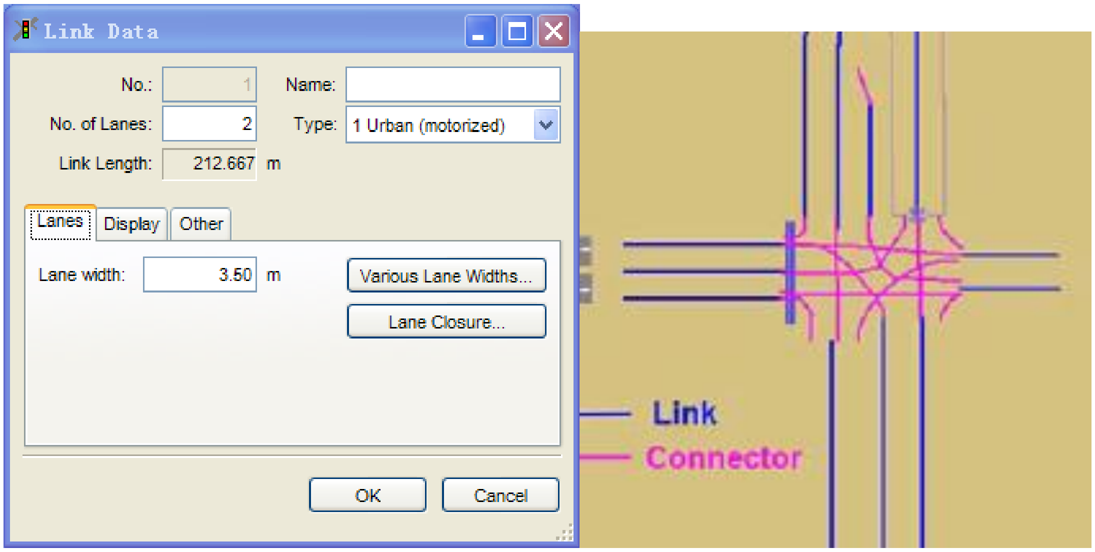
Figure 4 Background Settings in VISSIM



Links

Links in VISSIM represent freeway segments or road segments in actual world. Based on the background image, all those frontage roads and cross streets are coded into the model. In VISSIM, links can be defined with characteristics like number of lanes, lane width, link length and link type etc. It also provides Display options for users to define 3D demonstration factors, which is very useful if visualization is needed. Link type can impact vehicle behavior according to car-following and lane-changing theories.

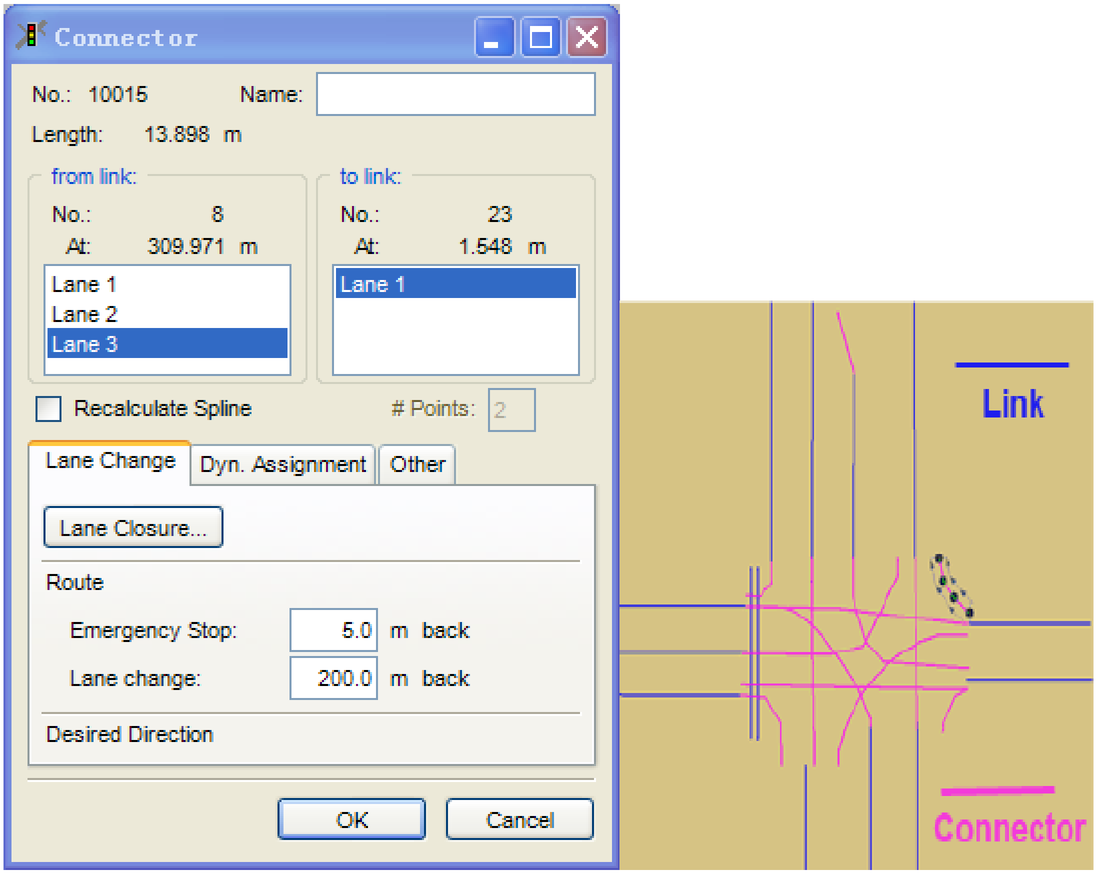
Figure 5 Links in VISSIM



<u>Connectors</u>

All those links have to be connected by connectors, for they can't connect with each directly in VISSIM. So connectors serve as joints between links. It can define from which lane connected to which lane. Plus, the "Route" option can define lane-changing parameters. "Recalculate Spline" option can help generate smoother curves for connection.

Figure 6 Connectors in VISSIM

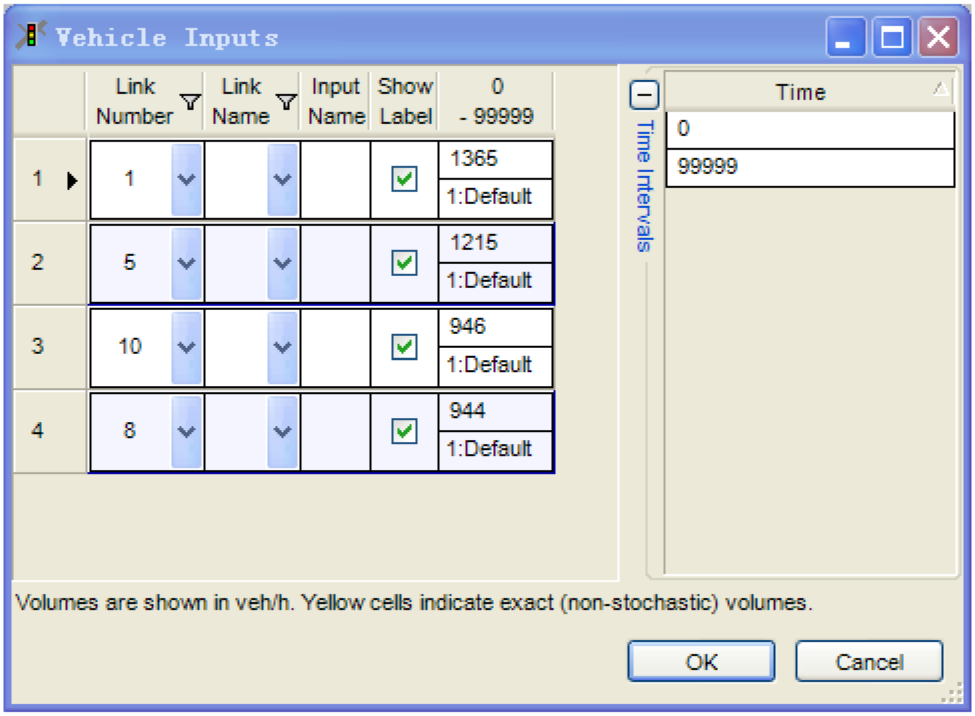


Traffic in Network

<u>Vehicle inputs</u>

Vehicle inputs can be defined at each edge of the network in VISSIM. Vehicle inputs parameters include traffic volume at each simulation time period, vehicle type, traffic composition, desire speed distribution etc. Those vehicles generated from those inputs will travel inside the network until meet the end of the network and disappear.

Figure 7 Vehicle Inputs in VISSIM

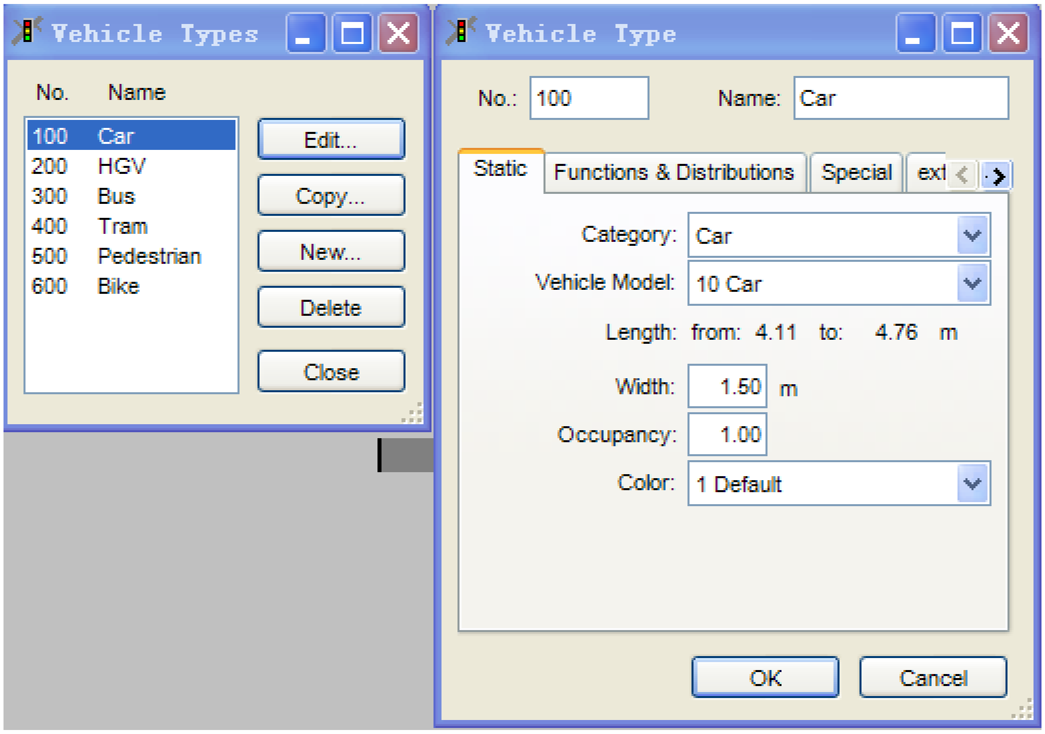


Vehicle type and class

In VISSIM, uses can define different vehicle types such as Car, HGV, Bus, Tram, Pedestrian, Bike etc. Those different types of vehicles will be treated differently in terms of driving behaviors. For each type of vehicle, we can define vehicle length, width, occupancy, acceleration rate and other characteristics.

One can also define vehicle class in VISSIM. A vehicle class may combine one or more previously defined vehicle types. For example, we can combine car and truck into one vehicle class: fast-moving traffic, and combine pedestrians and bikes into slow-moving traffic.

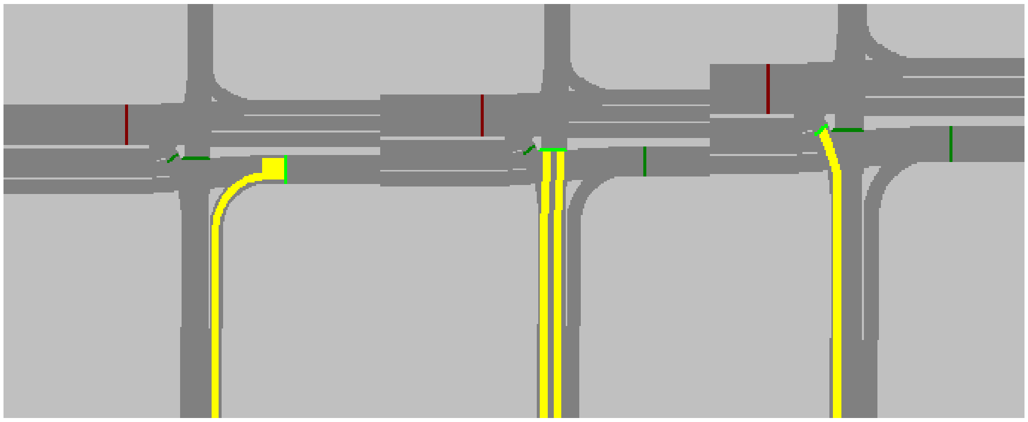
Figure 8 Vehicle Types in VISSIM



<u>Routes</u>

Routes in VISSIM are very essential parts in defining travelling path for each vehicle. Figure 9 shows the right turn, through, and left turn movements routes in the model. User can define associated turning percentage to each movement according to actual data. Vehicles generated from inputs will split based on those turning ratio and move on to their separated routes when they meet one of those route decision points.

Figure 9 Routes in VISSIM

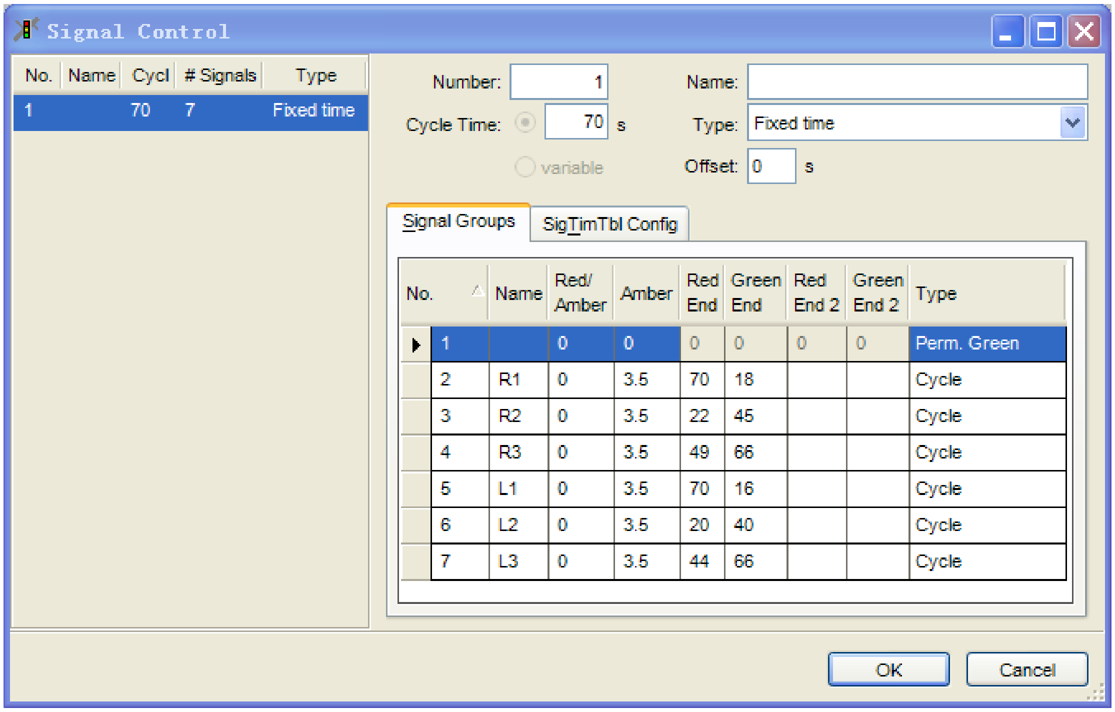


Traffic Control

Signal Controllers

One common way of traffic control is signal control. In VISSIM, one can use different types of signal controllers such as fixed time, NEMA, VAP etc. In this study, fixed time signal controller is used. For signal controller, one can define its cycle length, offset and green/red end etc. After defining those controller parameters, we have to build signal heads for each lane at intersections. For those signal heads, one can define which signal controller it's using, which signal group it's on (which phase), and the control type (circular or arrow).

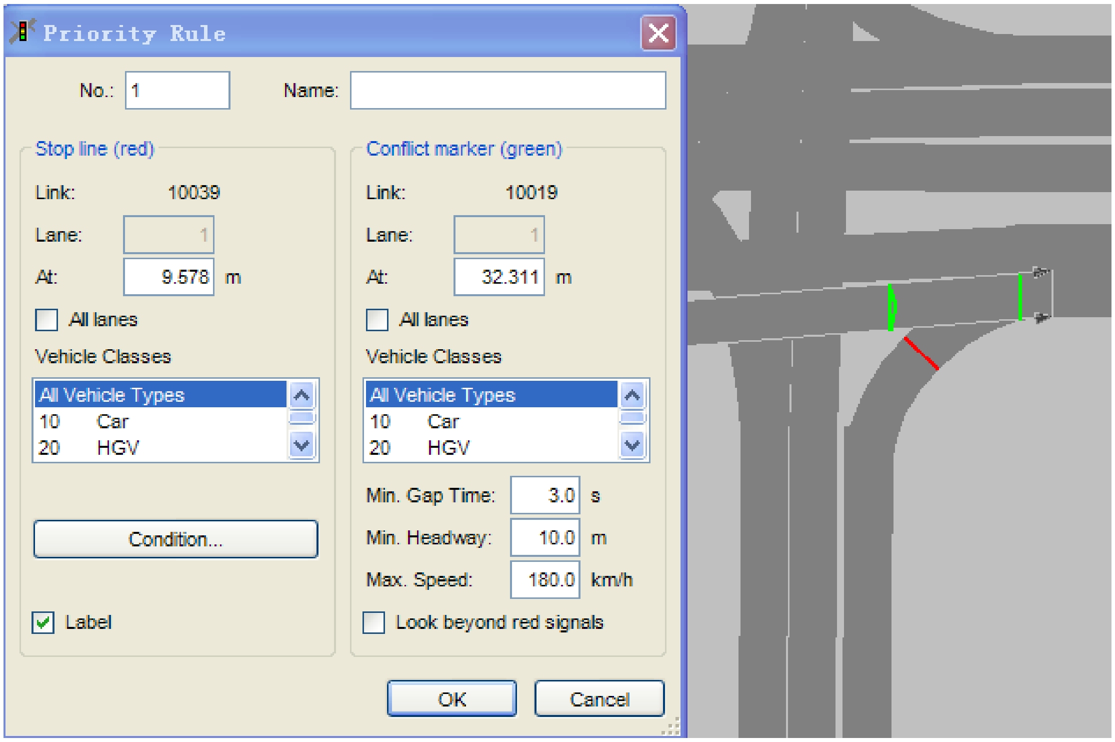
Figure 10 Signal Controllers in VISSIM



Priority Rule

Another traffic control approach is priority rule in VISSIM. Usually, priority control approach is used at non-signalized intersections or at separating or joining links. In this study, all intersections are signalized, but priority rule is still used to avoid confliction when dealing with right turn movements and permitted left turn movements.

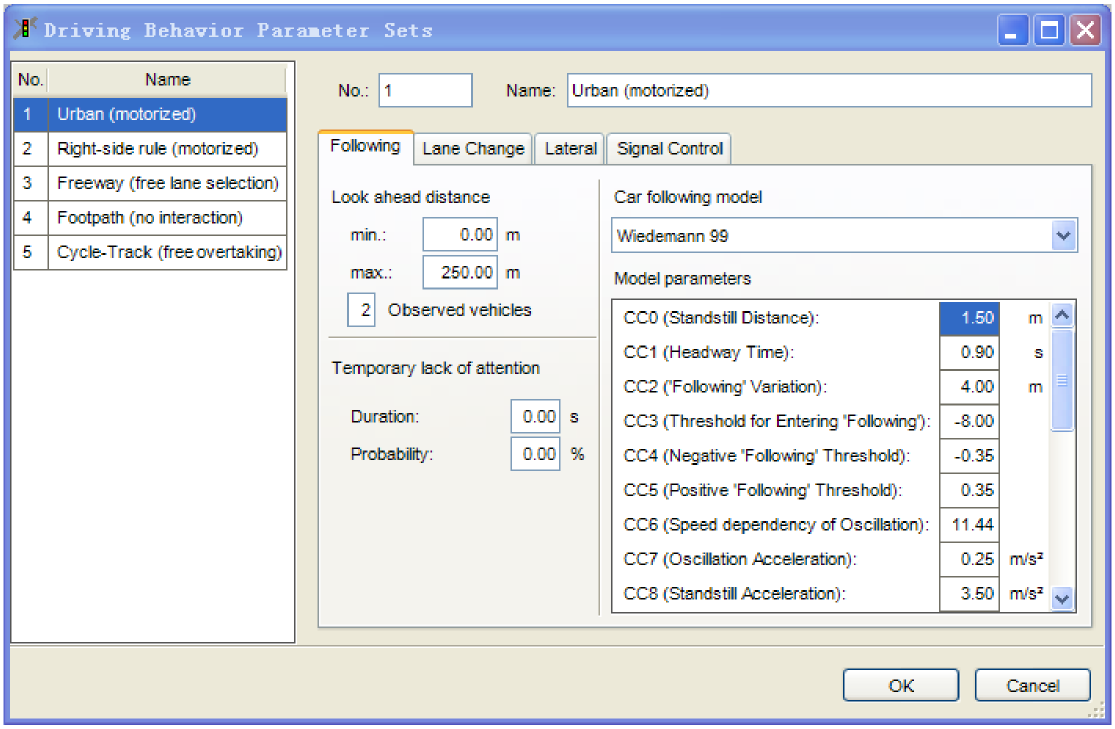
Figure 11 Priority Rule in VISSIM



Driving Behavior

VISSIM is a microscopic traffic simulation, which controls the driving behavior of individual vehicles based on car-following and lane-changing models. Figure 12 shows the driving behavior sets in VISSIM. There are five different types of driving behavior categorized based on the link types (i.e. Urban, Right-side rule, Freeway, Footpath and Cycle-Track). In this study, only Urban (motorized) type of driving behavior is used. All those parameters in car-following and lane-changing model are adjustable. And they will be adjusted in the calibration process to generate a simulation model closer to reality.

Figure 12 Driving Behavior Parameters in VISSIM



3.4 Simulation Model Calibration

Sensitivity Analysis

Too many parameters in VISSIM are adjustable, and it is a really intimidating work if we take all those parameters into consideration. Thus, it is desirable to reduce the amount of parameters needed to be calibrated. In this study, a sensitivity analysis is conducted to find out those parameters that impose the most influence on simulation model. This way, we can improve the efficiency of calibration.

Parameters that can be calibrated in VISSIM

A large number of parameters in VISSIM are adjustable, and those parameters are listed in table 1. Some other parameters that are obviously indifferent are excluded, such as lateral behavior and reaction to amber signals.

Table 1 Adjustable Parameters in VISSIM

Parameter Name		**Default**	**Unit**	**Change scale of parameter**
Car Following Model				
Look ahead distance	Max.	250	m	100~300
	Observed vehicles	2		1~4
Wiedemann 99 Model parameters	CC0	1.5	m	1~5
	CC1	0.90	s	0.5~2.0
	CC2	4.00	m	2~10
	CC3	-8.00		-15~-3
	CC4	-0.35		-0.7~-0.1
	CC5	0.35		0.1~0.7
	CC6	11.44		5~20
	CC7	0.25	m/s^2	0.1~1.0
	CC8	3.50	m/s^2	2.5~7
	CC9	1.50	m/s^2	0.5~ 6

Table 1 Continued

Parameter Name		**Default**	**Unit**	**Change scale of parameter**
Lane Changing Model				
Own	Maximum deceleration	-4.00	m/s^2	-5~-1
	-1 m/s^2 per distance	200	m	50~300
	Accepted deceleration	-1.00	m/s^2	-1.50~-0.10
Trailing vehicle	Maximum deceleration	-3.00	m/s^2	-5~-1
	-1 m/s^2 per distance	200	m	50~300
	Accepted deceleration	-0.50	m/s^2	-1.50~-0.10
Waiting time before diffusion		60	s	20~60
Minimum headway		0.5	m	0.5~7.0
Route	Emergency stop	5	m	5~10
	Lane change	200	m	100~250
Desired speed distribution	Mean	60	km/h	60~90
	Standard deviation	10	km/h	5~15

Paired t-test

In order to conduct sensitivity analysis, we change the value of parameters in table 1 and conduct multi-runs. In this study, each time we increase the value of parameters 30% of their default values. And for each parameter, we run the simulation with different random seeds for 10 times. Average travel speed is used as the performance measure in this study. Then we compare the results with changed parameters to the results with default parameters using paired t-test. This way, sensitive parameters can be found.

The paired t-test is designed to handle correlation among matched pairs of measurements or data points *(Spiegelman, 2004)*. In this case, each time only the target parameter varies and other elements remain the same, so the assumption of paired t-test applies. Moreover, when the scatter plot of those two group outputs is plotted, a linear trend can be found. Therefore, paired t-test is the best choice for comparison of default outputs and changed outputs here.

Each time, we change one target parameter and run the simulation for 10 times. So for 24 parameters, altogether 240 runs are conducted. However, when we test whether the sample space of 10 for each parameter is sufficient using formula $n \geq \left(\frac{Z_{0.025} * \sigma}{r * \mu}\right)$, for most parameters 10 times multi-run is not enough. Because of time limit, here we assume 10 times multi-run is good for all parameters. So paired t-test results are shown as follow:

Table 2 Paired t-test Results for Analysis of Sensitivity

Parameter Name		Default value	Changed value	Average output change (%)	P value
Car Following Model					
Look ahead distance	Max.	250	325	1.56	0.23
	Observed vehicles	2	3	1.98	0.28
Wiedemann 99	CC0	1.5	1.95	4.71	0.00
	CC1	0.9	1.17	3.08	0.23
	CC2	4	5.2	5.56	0.00
	CC3	-8	-10.4	0.24	0.84
	CC4	-0.35	-0.455	0.42	0.75
	CC5	0.35	0.455	0.23	0.86
	CC6	11.44	14.872	1.46	0.50
	CC7	0.25	0.325	1.17	0.40
	CC8	3.5	4.55	0.11	0.93
	CC9	1.5	1.95	2.59	0.03

Table 2 Continued

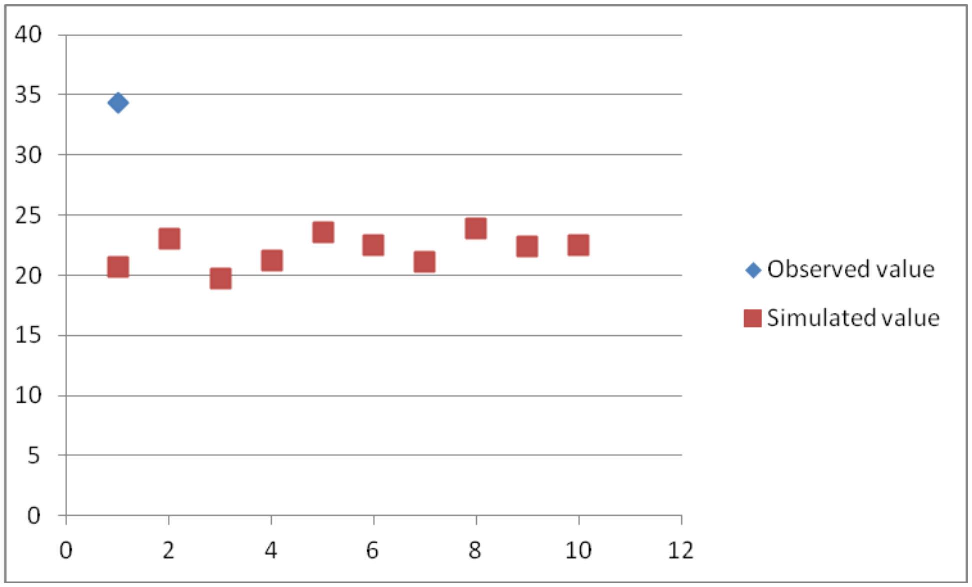
Lane Changing Model					
Own	Maximum deceleration	-4	-5.2	2.48	0.23
	1m/s^2 per distance	200	260	1.37	0.18
	Accepted deceleration	-1	-1.3	1.73	0.31
Trailing vehicle	Maximum deceleration	-3	-3.9	2.80	0.08
	1m/s^2 per distance	200	260	2.01	0.09
	Accepted deceleration	-0.5	-0.65	1.87	0.10
Minimum headway		0.5	0.65	1.16	0.35
Route	Emergency stop	5	6.5	1.49	0.06
	Lane change	200	260	2.67	0.08
Desired speed distribution	Mean	60	78	7.72	0.00
	Deviation	10	13	0.15	0.92

In statistics, those parameters with small p-values are significantly different, which means they are sensitive parameters. In this study, if choose type I error (i.e. α) as 0.05, four parameters can be found as having a significant impact on simulation model. But none of those four parameters is related to lane-changing. So, we choose 0.10 as type I error. This way, eight parameters are sensitive: CC0, CC2, CC9, Maximum deceleration and reduction rate for trailing vehicle, emergency stop, lane change starting point and the mean of desired speed distribution. In table 2, those eight sensitive parameters are marked in red.

Initial Evaluation

This step is to test whether default parameters in the simulation model is sufficient to represent field data. Simulation model with default parameters values is run for 10 times and compared to field data.

Figure 13 Initial Evaluation Using Default Parameters



From figure 13, clearly the observed data is not within the range of simulated outcomes. So default parameters can't reasonably represent field conditions. Calibration is needed.

Calibrating Selected Parameters

The calibration process includes three parts. 1) Identify calibration parameters and their acceptable ranges, 2) conduct statistical experimental design and generate reasonable number of parameters sets, 3) conduct multi-run for each parameter set and find the most feasible one.

<u>Identification of calibration parameters</u>

VISSIM provides so many adjustable parameters that it is almost impossible to calibrate all of them. In this study, we only calibrate those sensitive parameters identified in the sensitivity analysis mentioned previously. Those eight sensitive parameters and their acceptable ranges are listed in table 3.

Table 3 Sensitive Parameters and Acceptable Range

Parameter Name	ID	Unit	Acceptable Range
CC0	P1	m	1~5
CC2	P2	m	2~10
CC9	P3	m/s^2	0.5~6
Maximum Deceleration	P4	m/s^2	-5~-1
Decelerate Resolution	P5	m	50~300
Emergency Stop	P6	m	5~10
Lane Change	P7	m	100~250
Mean of Desired Speed	P8	Km/h	60~90

Conduct statistical experimental design and generate parameter sets

Considering eight sensitive parameters and their acceptable ranges listed in table 3, it is impossible to evaluate all those parameter combinations. Thus a statistical experimental design is desirable to reduce parameters sets needed to evaluate. In this study, Latin Hypercube Sampling Method is applied.

Latin Hypercube Sampling Method is a space-filling design method that can spread the points as evenly as possible around the operating space. This design should be used when there is little or no information about the underlying effects of factors on responses. LHS method is coded in JMP for use, and in this study, it generates 20 parameter sets for feasibility test.

Table 4 Parameter Sets Generate by LHS Method

	P1	P2	P3	P4	P5	P6	P7	P8
1	1.0	3.7	6.0	-2.9	50.0	10.0	147.4	85.3
2	1.4	10.0	4.8	-1.0	76.3	8.2	178.9	83.7
3	1.2	7.5	3.1	-2.3	155.3	6.6	100.0	61.6
4	3.1	5.4	5.7	-4.2	89.5	9.5	123.7	60.0
5	2.7	3.3	3.7	-3.9	168.4	9.2	210.5	82.1
6	3.7	9.6	1.1	-2.7	207.9	8.9	242.1	69.5
7	2.1	7.1	2.2	-3.5	63.2	9.7	218.4	78.9
8	4.4	6.2	2.5	-1.4	102.6	7.6	234.2	86.8
9	1.8	2.8	1.4	-1.6	221.1	7.1	155.3	72.6
10	2.5	7.9	1.9	-1.2	115.8	8.7	186.8	75.8
11	3.5	4.1	4.6	-4.8	234.2	6.3	163.2	74.2
12	4.2	9.2	5.1	-4.4	128.9	7.9	194.7	77.4
13	1.6	5.8	4.0	-4.6	247.4	7.4	115.8	63.2
14	3.9	4.9	4.3	-2.5	286.8	5.3	131.6	71.1

Table 4 Continued

	P1	*P2*	*P3*	*P4*	*P5*	*P6*	*P7*	*P8*
15	2.3	2.4	5.4	-3.3	142.1	6.1	107.9	80.5
16	3.3	8.7	2.8	-2.1	181.6	5.8	139.5	67.9
17	2.9	6.6	0.8	-1.8	260.5	5.5	226.3	90.0
18	4.8	4.5	3.4	-3.7	194.7	8.4	250.0	88.4
19	4.6	2.0	1.7	-5.0	273.7	6.8	171.1	66.3
20	5.0	8.3	0.5	-3.1	300.0	5.0	202.6	64.7

Determine the most feasible parameter set

For each parameter set, 5 times multi-run was conducted. The parameter set that generate the least discrepancy between simulated data and observed data is chosen as the most feasible parameter set and will be used in the simulation model. The optimal parameter set generated is shown in table 5:

Table 5 Calibrated Parameters Using GA

	P1	P2	P3	P4	P5	P6	P7	P8
Default	**1.5**	**4**	**1.5**	**-3**	**200**	**5**	**200**	**60**
Calibrated	**3.9**	**4.9**	**4.3**	**-2.5**	**287**	**5.3**	**132**	**71**

After calibration, the model developed in VISSIM will be ready for analysis.

CHAPTER IV

SIGNAL TIMING OPTIMIZATION

There are two reasons to optimize the signal timing strategies. First, optimized signal timing strategies can show the actual potential of each interchange design, and the researcher can focus on how traffic flow operates under different interchange designs by excluding the influence of signal timing. Second, this process can provide recommendations of the optimal timing strategies for those two interchange designs, especially the X-ramp interchange design.

To find the optimal signal timing for each scenario, the software package Synchro is used in the following procedures:

- Examine the two popular interchange timing strategies (TTI 4-phase and three-phase operation), and select the one that yields less delay
- Optimize cycle length
- Optimize green splits
- Left turn treatment, whether permitted left turn is allowed.

After all those procedures, an optimal signal timing plan can be generated for each scenario. The following is the procedures for signal timing optimization using Synchro.

4.1 Optimization Tool – Synchro

Synchro is a macroscopic analysis and optimization software in traffic engineering. It is very helpful in dealing with signal timing optimization problems. Synchro mainly utilizes the Highway Capacity Manual (HCM) methodology for signalized intersections. It can provide optimal solutions to some complicated situations such as three phase and four phase operation at a diamond interchange.

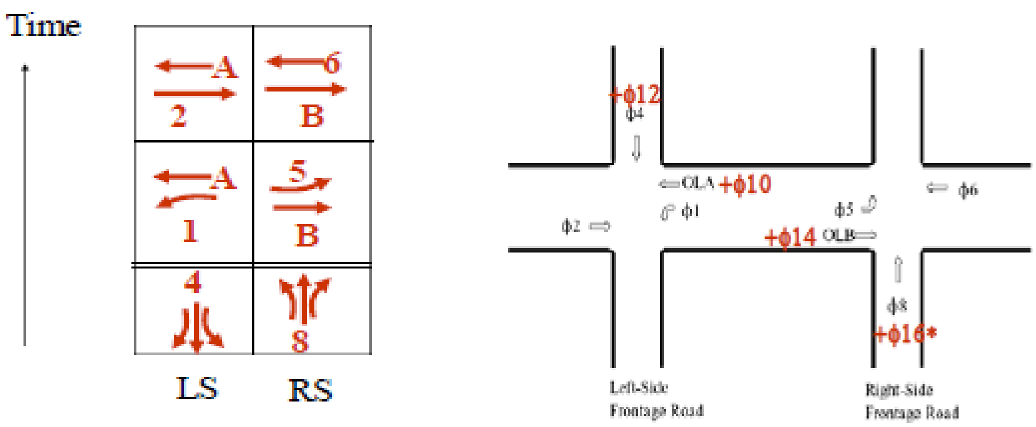
4.2 Signal Timing Strategies

Typically, there are two signal timing strategies recommended for diamond interchanges: Three-Phase Operation and Four-Phase Operation.

Three-Phase Operation

Figure 14 shows the three-phase timing plan for a diamond interchange and the numbering strategy for intersection movements. The figure shown is just a basic three-phase strategy with no overlapping, but three-phase operation can have overlaps. Also, this is a lead-lead situation, which means left turn movements phase is leading or before the through movements phase. Lag-lag situation is another option.

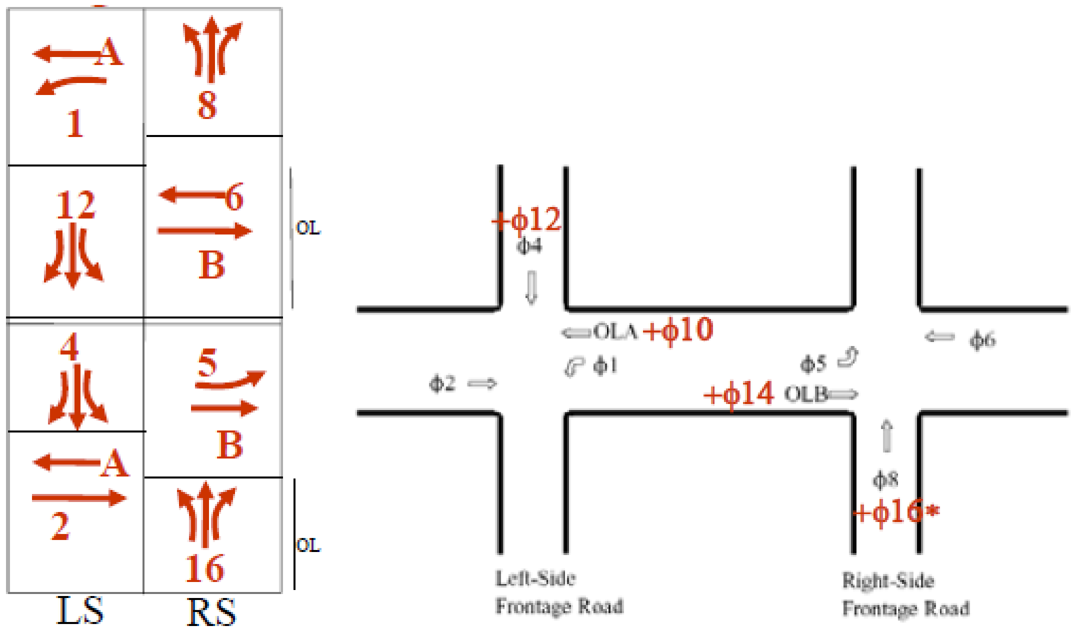
Figure 14 Three-Phase Operations



Four-Phase Operation

Figure 15 shows the four-phase timing plan for a diamond interchange and the numbering strategy for intersection movements. The major benefit of the four-phase operation is that, if properly timed, hardly any movement has to stop inside the intersection. This is a huge advantage especially for those tight diamonds where the left side intersection and right side intersection are too close together that queue storage is a problem. However, four-phase operation has its disadvantage. Comparing to three-phase, four-phase has one more phase each cycle, which means more lost time for each cycle. Thus, four-phase operation typically associates with less capacity.

Figure 15 Four-Phase Operations



Both the three-phase and four-phase operation strategies have been coded into Synchro as signal timing examples, so we only have to modify some parameters (such as traffic volumes, road length, etc.) and they can be ready for analysis.

4.3 Cycle Length Optimization

According to Webster, the relationship between delay and cycle length is a convex function. When cycle length increases, the general delay during each cycle increases, on the other hand, when cycle length decreases, the lost time percentage increases, and the capacity of this intersection drops. Therefore, there exists an optimal cycle length that can generate minimum delay for a specific intersection. With the help of Synchro, the optimization of cycle length is pretty simple. After modifying associated parameters both in four-phase operation scenario and three-phase operation scenario, by pushing the Optimize button for cycle length, Synchro will automatically calculate the delay and generate the optimal cycle length for you.

4.4 Phase Split Optimization

The method Synchro uses to optimize phase split is based on the equal degree saturation approach. This approach will allocate green time to each critical movement in proportion to its percentage. Critical movements are those with the highest volume to saturation flow ratio per phase. To optimize phase split in Synchro is simple too, just click the Optimize button near the phase split option. The results may have overlap situation if necessary.

4.5 Left Turn Treatment

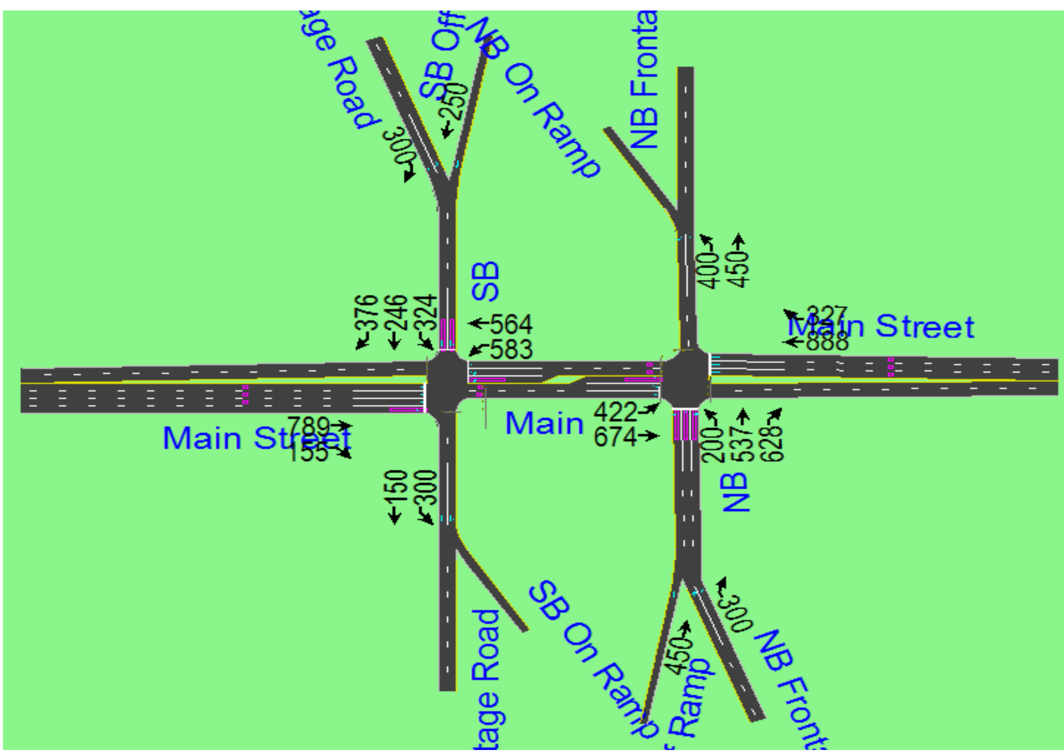
The left turn treatment options can be protected only, protected plus permitted, or permitted only. In Synchro, it is not very hard to set those three left turn treatment options and not hard to evaluate either. Also, it provides those three options for each left turn movements, so we can set different treatment for different left turn movements. In most scenarios of this study, permitted only is not a good option because of the heavy opposing through traffic. Also, for the same reason, protected plus permitted has very limited advantage over protect only option.

4.6 Case Study Example

To illustrate the above procedure, the case study of SH6 @ Harvey Road interchange is selected as a signal timing optimization example. Figure 16 shows the model in Synchro with all those traffic volume inputs. And to optimize the signal timing plan, the following procedure is used in the software package Synchro:

- Examine the two popular interchange timing strategies (TTI four-phase and three-phase operation)
- Optimize cycle length
- Optimize green splits
- Left turn treatment.

Figure 16 Network Information in Synchro



By following the optimization procedure, all the delays calculated after each step is shown in the table below:

Table 6 Summary of the Optimization Procedure

Optimizing Step	Four-Phase	Three-Phase
Setting Strategies	43.2	39.4
Cycle Length	36.9	24.1
Green Split	36.9	24.1
Left Turn Treatment	35.7	23.6

Therefore, by comparing the final results, we can find that the optimized Three-Phase Operation can generate less delay. Figure 17 is the optimized signal timing plan for the interchange.

Figure 17 Signal Timing Plan for the SH6 @ Harvey Rd Interchange

CHAPTER V

MODEL ANALYSIS

5.1 Experimental Design

Varying Factors in Experimental Design

To explicitly investigate the advantage and disadvantage of ramp reversal, as well as the impact of traffic demand pattern on interchange operations, a thorough simulation analysis is needed. Thus, different scenarios will be created based on this purpose. Since interchanges normally are symmetric, in this study, only one side will be investigated and the other side is assumed to be the same condition to simplify the analysis.

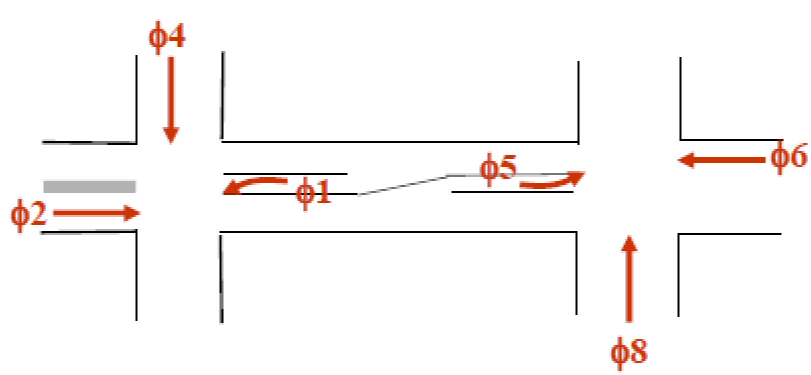
Following five major factors will be changed when designing different scenarios:

1) Interchange design. In order to study the best suitable interchange design under different situations, the researcher plan to carry out ramp reversal based on the initial diamond interchange.
2) Demand patterns. In order to examine the impact of traffic demand pattern on interchange operations, different OD patterns need to be designed. What actually matters is the exiting demand around the interchange. So in this study, the attraction area's location is changing from downstream the intersection to upstream the intersection.
3) Demand level. The demand level here is mainly in reference to the attraction or the exiting volume from the freeway.

4) Flow on frontage road intersection (the flow resulting from exiting demand is not included). To measure the operation of frontage road and crossing street intersection, the sum of degree of saturation of all critical lane groups is used. By changing the saturation rate of the signalized intersection, the researcher can analyze the impact of the flow on frontage road and crossing street.
5) Turning movements' percentage of critical movements.

As shown in figure 18, movements 4 and 8 are essential in this study and their hourly volume during peak period would be a changing factor. Also, the percentage of turning movements of phase 4 and 8 would be a varying factor. The relative ratio of all the other movements would be held constant to simplify our problem.

Figure 18 Diamond Interchange Movement/Phase



Thus the varying factors that will be used in experimental design and their range (minimum value to maximum value) are summed up in table 7:

Table 7 Factors in Experimental Design

Factors	**Measurement**	**Varying Range**	
		Minimum	**Maximum**
Demand at the intersection	$\sum \frac{V}{C}$	0.4	1.0
Peak hour volume for phase 4 and 8	Veh/hr/ln	200	600
Percentage of the through movement for phase 4 and 8	%	20	80

Latin Hypercube Design

A space-filling design algorithm – Latin Hypercube Design is selected for this study to generate design points to bind the bias in this experiment. Latin Hypercube Design *(SAS Institute Inc. 2007)* chooses points to maximize the minimum distance between design points but with a constraint. The constraint maintains the even spacing between factor levels. Since LHD can't handle categorical factors, three continuous factors in table 7 and their varying ranges are input to statistical software JMP. The following table summarizes all the design points considering only continuous factors:

Table 8 Latin Hypercube Design

Scenarios	**Volume**	$\sum \frac{V}{C}$	**Through Percentage**
1	600	0.72	26
2	453	0.75	39
3	474	0.56	23
4	558	0.53	42
5	347	0.94	33
6	305	0.87	80
7	495	0.84	77
8	389	0.59	74
9	263	0.62	45
10	579	0.81	55
11	284	0.40	64
12	368	0.78	58
13	200	0.91	52
14	537	0.49	67
15	432	0.43	48
16	242	0.68	20
17	221	0.65	71
18	326	0.46	29
19	516	0.97	36
20	411	1.00	61

Simulation Scenarios

Since Latin Hypercube Design can't deal with categorical factors, table 8 didn't include interchange type factor into consideration. However, this factor is essential in our study and can't be ignored. Thus, this categorical factor has to be crossed with the design generated from the previous step. Also, we need to be careful when constructing those scenarios, especially when dealing with the traffic volume on frontage road at X-ramp interchange. Because in X-ramp situations, most of the traffic will have to remain on the freeway until meet the exit ramp downstream. So the traffic volume will be greatly reduced at the frontage road.

In this study, first of all, we assume 50% of the original traffic will remain on the frontage road after the ramp reversal. Scenarios 21 to 40 are constructed based on this. Then, we assume the 90% of the original traffic are from the upstream exit ramp in the diamond interchange design for simplification. Therefore, all those traffic volume on frontage road in scenarios 41 to 60 will only be 10% of what it used to be. Table 9 summarizes the new 60 scenarios that will be used in simulation analysis.

Table 9 Simulation Scenarios Summary

Scenarios	**Type**	**Volume**	**V/C**	**Percentage**
1	1	600	0.72	26
2	1	453	0.75	39
3	1	474	0.56	23
4	1	558	0.53	42
5	1	347	0.94	33
6	1	305	0.87	80
7	1	495	0.84	77
8	1	389	0.59	74

Table 9 Continued

Scenarios	Type	Volume	V/C	Percentage
9	1	263	0.62	45
10	1	579	0.81	55
11	1	284	0.40	64
12	1	368	0.78	58
13	1	200	0.91	52
14	1	537	0.49	67
15	1	432	0.43	48
16	1	242	0.68	20
17	1	221	0.65	71
18	1	326	0.46	29
19	1	516	0.97	36
20	1	411	1.00	61
21	2	300	0.72	26
22	2	226	0.75	39
23	2	237	0.56	23
24	2	279	0.53	42
25	2	174	0.94	33
26	2	153	0.87	80
27	2	247	0.84	77
28	2	195	0.59	74
29	2	132	0.62	45
30	2	289	0.81	55
31	2	142	0.40	64
32	2	184	0.78	58
33	2	100	0.91	52
34	2	268	0.49	67

Table 9 Continued

Scenarios	**Type**	**Volume**	**V/C**	**Percentage**
35	2	216	0.43	48
36	2	121	0.68	20
37	2	111	0.65	71
38	2	163	0.46	29
39	2	258	0.97	36
40	2	205	1.00	61
41	2	60	0.72	26
42	2	45	0.75	39
43	2	47	0.56	23
44	2	56	0.53	42
45	2	35	0.94	33
46	2	31	0.87	80
47	2	49	0.84	77
48	2	39	0.59	74
49	2	26	0.62	45
50	2	58	0.81	55
51	2	28	0.40	64
52	2	37	0.78	58
53	2	20	0.91	52
54	2	54	0.49	67
55	2	43	0.43	48
56	2	24	0.68	20
57	2	22	0.65	71
58	2	33	0.46	29
59	2	52	0.97	36
60	2	41	1.00	61

* In table 9, Type 1 indicates Diamond Interchange;

Type 2 indicates X-ramp Interchange.

5.2 Simulation Runs for Each Scenario

Computer based simulation software – VISSIM has some randomness involved. The Random Seed parameter setting in VISSIM is designed to generate random inputs to mimic real world situations. Thus, it is desirable to conduct multiple runs for each scenario to exclude the random influence. The following equation is used to estimate the minimum number of runs that needed in each scenario.

$$n^* \geq S^2(n)(z_{1-\alpha/2}/\beta)^2$$

Where, n – minimum number of runs for each scenario,

$S^2(n)$ – Variation of the sample,

$Z_{1-a/2}$ – Z-value, choose 1.96 in this study,

β – Precision, choose 5% of the mean in this study.

To use the above equation to estimate the number of runs needed, we have to conduct some initial runs. In this study, 20 initial runs are conducted. The results are summarized in table 10.

Table 10 Summary of Initial Runs

Seed	**Delay**	**Seed**	**Delay**
1	24.65	**11**	25.05
2	24.57	**12**	24.68
3	24.79	**13**	24.97
4	25.30	**14**	25.04
5	24.95	**15**	25.20
6	25.36	**16**	24.86
7	25.23	**17**	24.92
8	25.89	**18**	24.56
9	24.69	**19**	25.48
10	25.58	**20**	25.39
Average	25.06		
SDV	0.37		

Based on the average and standard deviation of those initial runs, we can estimate that the minimum number of simulation runs for each scenario is 9.

5.3 Additional Factors

To consider the full impact of ramp reversal, there are two other traffic groups needing to be taken into account. First, travelers with cross street destinations will need to get off freeway from the upstream interchange after ramp reversal. This is the negative impact resulting from ramp reversal. Second, travelers with downstream destinations will remain on freeway until after the intersection. This is the positive impact resulting from ramp reversal.

We didn’t include those two factors in the experimental design because they only will make the situation much more complicated. With the time constraint, we can’t conduct more simulation runs to consider those two traffic groups. Thus, a better way to go around is to make some assumptions and separate them from the simulation scenarios.

For those travelers remaining on freeway, they benefit by avoiding one signal. So the benefit of those travelers can be assumed to be the average control delay at the intersection. For those travelers getting off the freeway early, the cost can be assumed to be the difference of freeway travel time and frontage road travel time plus the right-turn delay at the intersection. The right-turn delay can be approximated by assuming those vehicles will experience the same delay as the average right-turn delay in simulation model.

5.4 Simulation Results

Signal Timing Optimization Results

There are two reasons to optimize the signal timing strategies. First, optimized signal timing strategies can show the actual potential of each interchange design, and the researcher can focus on how traffic flow operates under different interchange designs by excluding the influence of signal timing. Second, this process can provide recommendations of the optimal timing strategies for those two interchange designs, especially the X-ramp interchange design.

So before we analyze those 60 scenarios in VISSIM, we have to find the optimal signal timing plan for each scenario. The procedure of finding the optimal signal timing plan is explained explicitly in chapter 4. The following table summarizes the strategy that will be used for each scenario.

Table 11 Summary of Signal Timing Strategies

Scenarios	**Signal**	**Scenarios**	**Signal**	**Scenarios**	**Signal**
1	4p	**21**	3p	**41**	3p
2	3p	**22**	3p	**42**	3p
3	3p	**23**	3p	**43**	3p
4	4p	**24**	3p	**44**	3p
5	3p	**25**	3p	**45**	3p
6	3p	**26**	3p	**46**	3p
7	4p	**27**	4p	**47**	3p
8	4p	**28**	4p	**48**	3p
9	3p	**29**	3p	**49**	3p
10	3p	**30**	3p	**50**	3p
11	4p	**31**	4p	**51**	4p
12	3p	**32**	3p	**52**	3p
13	3p	**33**	3p	**53**	3p
14	4p	**34**	3p	**54**	3p
15	4p	**35**	4p	**55**	4p
16	3p	**36**	3p	**56**	3p
17	4p	**37**	3p	**57**	3p
18	3p	**38**	4p	**58**	4p
19	4p	**39**	3p	**59**	3p
20	3p	**40**	3p	**60**	3p

* In table 11, Signal 4p indicates Four-Phase Operation,

Signal 3p indicates Three-Phase Operation.

In table 11, we can find that for most cases, Three-Phase Operation is a better strategy. Only 17 scenarios out of those 60 scenarios will better off with Four-Phase Operation. Among those 17 scenarios, we can group them into two categories according to the reason why four-phase is suitable for them.

The first group includes scenarios 4, 11, 14, 15, 31, 35, 38, 51, 55, 58. Those scenarios share one thing in common. That is they all have very low degree of saturation (below 0.6). This means four-phase operation is more suitable for intersections with lower degree of saturation. This is because four-phase operation can provide smoother traffic movement inside the interchange and thus generate less overall delays, but with one more phase each cycle comparing to three-phase operation, it will have one more lost time each cycle thus when traffic demand increases at the interchange, the delay will increase significantly.

The second group includes scenarios 1, 7, 8, 17, 19, 27, 28. Those scenarios all have very high turning movements at the frontage road (above 65%). This could mean that four-phase operation also works well when the turning movements (especially left turns) are high. This is mainly because four-phase operation can provide a smoother movement and hardly any vehicle needs to stop inside the intersections if properly timed.

VISSIM Results

To investigate the difference between diamond interchange and X-ramp interchange, 60 scenarios are studied using simulation software – VISSIM. Each scenario is run for 9 times with different random seed. Table below summarizes the simulation study:

Table 12 Summary of VISSIM Results

Scenarios	Type	Volume	V/C	Percentage	Signal	Delay
1	1	600	0.72	26	4p	51.8
2	1	453	0.75	39	3p	23.5
3	1	474	0.56	23	3p	23.7
4	1	558	0.53	42	4p	23.3
5	1	347	0.94	33	3p	24.5
6	1	305	0.87	80	3p	29.0
7	1	495	0.84	77	4p	29.6
8	1	389	0.59	74	4p	23.8
9	1	263	0.62	45	3p	21.4
10	1	579	0.81	55	3p	25.1
11	1	284	0.40	64	4p	21.0
12	1	368	0.78	58	3p	24.9
13	1	200	0.91	52	3p	24.3
14	1	537	0.49	67	4p	26.1
15	1	432	0.43	48	4p	22.0
16	1	242	0.68	20	3p	21.4
17	1	221	0.65	71	4p	23.1
18	1	326	0.46	29	3p	20.2

Table 12 Continued

Scenarios	Type	Volume	V/C	Percentage	Signal	Delay
19	1	516	0.97	36	4p	30.6
20	1	411	1.00	61	3p	26.7
21	2	300	0.72	26	3p	43.9
22	2	226	0.75	39	3p	23.4
23	2	237	0.56	23	3p	22.9
24	2	279	0.53	42	3p	23.1
25	2	174	0.94	33	3p	26.2
26	2	153	0.87	80	3p	24.5
27	2	247	0.84	77	4p	25.3
28	2	195	0.59	74	4p	23.7
29	2	132	0.62	45	3p	26.3
30	2	289	0.81	55	3p	22.7
31	2	142	0.40	64	4p	23.6
32	2	184	0.78	58	3p	24.8
33	2	100	0.91	52	3p	26.2
34	2	268	0.49	67	3p	23.2
35	2	216	0.43	48	4p	24.1
36	2	121	0.68	20	3p	24.3
37	2	111	0.65	71	3p	23.6
38	2	163	0.46	29	4p	23.1
39	2	258	0.97	36	3p	25.8
40	2	205	1.00	61	3p	25.1
41	2	60	0.72	26	3p	41.9
42	2	45	0.75	39	3p	22.7
43	2	47	0.56	23	3p	21.6
44	2	56	0.53	42	3p	21.4

Table 12 Continued

Scenarios	**Type**	**Volume**	**V/C**	**Percentage**	**Signal**	**Delay**
45	2	35	0.94	33	3p	25.0
46	2	31	0.87	80	3p	23.8
47	2	49	0.84	77	3p	23.8
48	2	39	0.59	74	3p	21.7
49	2	26	0.62	45	3p	22.3
50	2	58	0.81	55	3p	20.6
51	2	28	0.40	64	4p	21.4
52	2	37	0.78	58	3p	23.0
53	2	20	0.91	52	3p	24.4
54	2	54	0.49	67	3p	21.1
55	2	43	0.43	48	4p	21.6
56	2	24	0.68	20	3p	22.1
57	2	22	0.65	71	3p	21.9
58	2	33	0.46	29	4p	20.9
59	2	52	0.97	36	3p	24.6
60	2	41	1.00	61	3p	24.1

* In table 12, Type 1 indicates Diamond Interchange;

Type 2 indicates X-ramp Interchange.

Signal 4p indicates Four-Phase Operation,

Signal 3p indicates Three-Phase Operation.

Besides those four factors considered in the simulation study, we have another two groups of traffic left out for the reason of simplifying our experiment. Now we have to include those two groups of traffic. First, travelers with cross street destinations will need to get off freeway from the upstream interchange after ramp reversal. This is the negative impact resulting from ramp reversal. Second, travelers with downstream destinations will remain on freeway until after the intersection. This is the positive impact resulting from ramp reversal.

For those travelers remaining on freeway, they benefit by avoiding one signal. So the benefit of those travelers can be assumed to be the average control delay at the intersection. For those travelers getting off the freeway early, the cost can be assumed to be the difference of freeway travel time and frontage road travel time plus right-turn delay at the intersection. The right-turn delay can be approximated by assuming those vehicles will experience the same delay as the average right-turn delay in simulation model.

But this is assuming that those travelers won't have to go through the upstream intersection, which means that the upstream interchange have to be X-ramp interchange. The table below summarizes the revised delay for X-ramp design after considering those two groups of traffic.

Table 13 Revised Results for X-ramp Interchange

Scenarios	Type	Volume	V/C	Percentage	Signal	Delay
21	2	300	0.72	26	3p	48.3
22	2	226	0.75	39	3p	26.3
23	2	237	0.56	23	3p	27.9
24	2	279	0.53	42	3p	27.6
25	2	174	0.94	33	3p	28.3
26	2	153	0.87	80	3p	25.1
27	2	247	0.84	77	4p	26.3
28	2	195	0.59	74	4p	25.1
29	2	132	0.62	45	3p	28.4
30	2	289	0.81	55	3p	25.0
31	2	142	0.40	64	4p	25.8
32	2	184	0.78	58	3p	26.4
33	2	100	0.91	52	3p	27.2
34	2	268	0.49	67	3p	25.8
35	2	216	0.43	48	4p	28.2
36	2	121	0.68	20	3p	26.9
37	2	111	0.65	71	3p	24.5
38	2	163	0.46	29	4p	27.3
39	2	258	0.97	36	3p	28.4
40	2	205	1.00	61	3p	26.4
41	2	60	0.72	26	3p	49.8
42	2	45	0.75	39	3p	27.9
43	2	47	0.56	23	3p	30.6
44	2	56	0.53	42	3p	29.4
45	2	35	0.94	33	3p	28.8
46	2	31	0.87	80	3p	24.9

Table 13 Continued

Scenarios	**Type**	**Volume**	**V/C**	**Percentage**	**Signal**	**Delay**
47	2	49	0.84	77	3p	25.7
48	2	39	0.59	74	3p	24.2
49	2	26	0.62	45	3p	26.0
50	2	58	0.81	55	3p	24.8
51	2	28	0.40	64	4p	25.4
52	2	37	0.78	58	3p	26.0
53	2	20	0.91	52	3p	26.2
54	2	54	0.49	67	3p	25.8
55	2	43	0.43	48	4p	28.9
56	2	24	0.68	20	3p	26.7
57	2	22	0.65	71	3p	23.6
58	2	33	0.46	29	4p	28.5
59	2	52	0.97	36	3p	29.2
60	2	41	1.00	61	3p	26.4

* In table 13, Type 2 indicates X-ramp Interchange.

Signal 4p indicates Four-Phase Operation,

Signal 3p indicates Three-Phase Operation.

Paired t-Test

Paired t-test is utilized here to compare those simulation results. Given two paired simulation results Xi and Yi of n values, the paired t-test determines whether they differ from each other in a significant way under the assumption that the paired differences are independent and identically normally distributed.

To apply the test, let

$$\hat{X}_i = (X_i - \overline{X})$$
$$\hat{Y}_i = (Y_i - \overline{Y}),$$

Then define t by

$$t = (\overline{X} - \overline{Y}) \sqrt{\frac{n(n-1)}{\sum_{i=1}^{n} (\hat{X}_i - \hat{Y}_i)^2}}$$

N is 9 in this study, and once t is found using the equations above, a p-value can be found using a table of values from student's t distribution. The confidence interval is selected as 90%. So if the p-value is below the threshold value for 90% CI, we can reject the null hypothesis and conclude that there is a significant difference between those two pairs.

By comparing those results using paired t-test, we can find that the following factors are essential when comparing diamond interchange with X-ramp interchange:

<u>Interchange Density</u>

Interchange density is the number of interchanges per mile. This is an important role because distance between two interchanges will be essential when calculating the delay caused by those vehicles getting off freeway early in order to reach the cross street destinations. In table 13, the results are calculating using the distance of 800 meters, which is the distance between two interchanges in the case study. After experimenting with some more numbers, we find that, for most cases, a distance more than one mile would cause too much delay, so ramp reversal is not beneficial when interchange density is low.

Upstream Interchange Design

This factor also will impact those vehicles with cross street destinations. If the upstream interchange type is diamond, those travelers have to take the exit ramp before upstream interchange intersection. So they will have to experience the control delay on the upstream intersection. On the other hand, if upstream interchange is X-ramp interchange, it will not increase overall delay. So X-ramp interchange is more desirable when upstream interchange type is also X-ramp design.

Traffic Volume on Frontage Road

By comparing scenarios 1, 7, 10, 14, 19 with 21, 27, 30, 34, 39 and 41, 47, 50, 54, 59, we can find that when traffic volume on frontage road is high, X-ramp interchange is better than Diamond interchange. The p value of this comparison is shown in table 14, and all those p values are smaller than 0.10 and indicate significant difference between comparison groups. This is because of two reasons. First, X-ramp interchange can redirect those vehicles through the freeway to the downstream exit ramp so that the demand on the intersections will be relieved. Second, those redirected traffic can also benefit from avoiding the intersection. Of course, this factor should be considered together with the movement percentage factor to have a better appreciation of scheme.

From the simulation results, ramp reversal is recommended when the traffic volume on frontage road is around 500 vehicles per hour per lane.

Table 14 Comparison Results 1

Comparison Scenarios Pairs		**P-value**
Scenario 1	**Scenario 21**	< 0.01
Scenario 7	**Scenario 27**	0.03
Scenario 10	**Scenario 30**	0.09
Scenario 14	**Scenario 34**	0.07
Scenario 19	**Scenario 39**	0.05
Scenario 1	**Scenario 41**	< 0.01
Scenario 7	**Scenario 47**	0.02
Scenario 10	**Scenario 50**	0.06
Scenario 14	**Scenario 54**	0.07
Scenario 19	**Scenario 59**	0.04

<u>Through Movement Percentage on Frontage Road</u>

Scenarios 6, 7, 14 and 26, 27, 34 and 46, 47, 54 clearly demonstrate the impact of through movement percentage. The p value of this comparison is shown in table 15, and all those p values are smaller than 0.10 and indicate significant difference between comparison groups. Basically, when through movement percentage is high, X-ramp interchange design is better. High through movement percentage means that more travelers' destinations are located downstream. As mentioned before, this factor should be considered together with the traffic volume factor. When both of them are high, which really means the downstream attraction is large; X-ramp interchange design is desirable. Ramp reversal is recommended when the through movement percentage is higher than 65.

Table 15 Comparison Results 2

Comparison Scenarios Pairs		**P-value**
Scenario 6	**Scenario 26**	0.01
Scenario 7	**Scenario 27**	0.03
Scenario 14	**Scenario 34**	0.07
Scenario 6	**Scenario 46**	0.01
Scenario 7	**Scenario 47**	0.02
Scenario 14	**Scenario 54**	0.07

Intersection Saturation Rate

Looking at scenarios 7, 10, 19 and 27, 30, 39 and 47, 50, 59, we can find that intersection saturation rate also plays an important role in determining whether a ramp reversal is needed. The p value of this comparison is shown in table 16, and all those p values are smaller than 0.10 and indicate significant difference between comparison groups. When the demand at the intersection is high (above 0.8 is recommended), ramp reversal will be beneficial because it can help keep many travelers remain on freeway and exit downstream to avoid going through the intersection.

Table 16 Comparison Results 3

Comparison Scenarios Pairs		P-value
Scenario 7	**Scenario 27**	0.03
Scenario 10	**Scenario 30**	0.09
Scenario 19	**Scenario 39**	0.05
Scenario 7	**Scenario 47**	0.02
Scenario 10	**Scenario 50**	0.06
Scenario 19	**Scenario 59**	0.04

CHAPTER VI

CONCLUSION AND RECOMMENDATIONS

6.1 Signal Timing Strategy Conclusions

To better explore the full potential of diamond interchange and X-ramp interchange, signal timing optimization has been conducted with the help of Synchro. After optimizing all those 60 scenarios, we conclude that for most cases, Three-Phase Operation is better than Four-Phase Operation, except for the following two situations:

- Degree of saturation is low (below 0.6). This means four-phase operation is more suitable for intersections with lower degree of saturation. This is because four-phase operation can provide smoother traffic movement inside the interchange and thus generate less overall delays, but with one more phase each cycle comparing to three-phase operation, it will have one more lost time each cycle thus when traffic demand increases at the interchange, the delay will increase significantly.
- Turning movements at the frontage road is high (above 65%). This could mean that four-phase operation also works well when the turning movements (especially left turns) are high. This is mainly because four-phase operation can provide a smoother movement and hardly any vehicle needs to stop inside the intersections if properly timed.

6.2 Ramp Reversal Conclusions

To investigate the benefit of ramp reversal, 60 scenarios have been run in VISSIM. And we conclude that the following factors need to be considered when comparing diamond interchange and X-ramp interchange:

1) Interchange density. The distance between two interchanges will play an important role when calculating the delay caused by those vehicles getting off freeway early in order to reach the cross street destinations. For most cases, a distance more than one mile would cause too much delay, so ramp reversal is not beneficial when interchange frequency is low.
2) Upstream interchange design. This factor also will impact those vehicles with cross street destinations. If the upstream interchange type is diamond, those travelers have to take the exit ramp before upstream interchange intersection. So they will have to experience the control delay on the upstream intersection. On the other hand, if upstream interchange is X-ramp interchange, it will not increase overall delay. So X-ramp interchange is more desirable when upstream interchange type is also X-ramp design.
3) Traffic volume on frontage road. This factor needs to be considered together with the movement percentage factor. But basically, when traffic volume on frontage road is high, a ramp reversal is beneficial. According to the simulation data, ramp reversal is recommended when the traffic volume on frontage road is around 500 vehicles per hour per lane.

4) Through movement percentage on frontage road. When through movement demand is high, which means more travelers' destinations are located downstream, X-ramp interchange design will be desirable. Ramp reversal is recommended when the through movement percentage is higher than 65.
5) Intersection saturation rate. When the demand at the intersection is high, ramp reversal will be beneficial because it can help keep many travelers remain on freeway and exit downstream to avoid going through the intersection. A saturation rate greater than 0.8 is recommended when considering ramp reversal.

6.3 Future Research Recommendations

This study has conducted a thorough investigation on comparing diamond interchange design with X-ramp interchange design, especially focused on the impact of traffic demand pattern and demand level. However, future research may still be needed in following aspects:

- Investigate more advanced signal timing strategies for interchanges, such as actuated signal timing,
- Focus more on the geometric factors' impact on ramp reversal,
- Consider more detailed and practical situations and develop a guideline for ramp reversal.

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